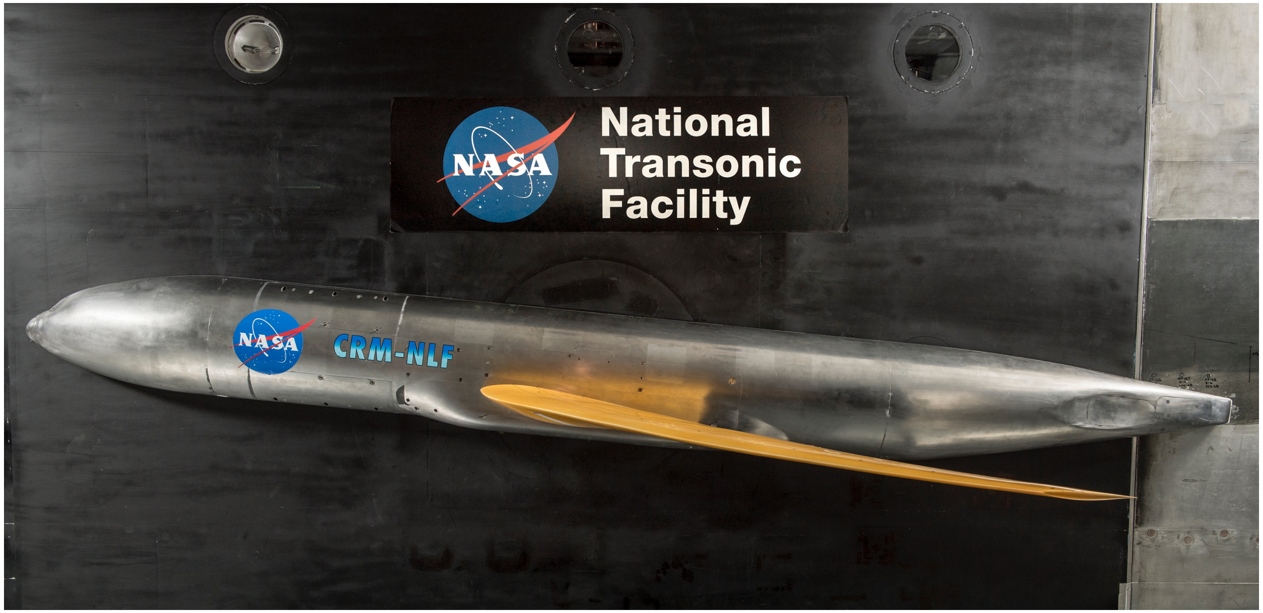
Design and Testing of the Common Research Model with Natural Laminar Flow



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NASA Langley Research Center

AIAA Transition Modeling Workshop • Virtual SciTech Forum • January 21-22, 2021

Outline

- Introduction
- Transition Delay Method and Model Design
- Experimental Setup
- Results and Discussions
  - General Results
  - Challenges with Data Analysis
    - Bypass Transition
    - Unsteady Shock
- Concluding Remarks

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Motivation

Natural laminar flow (NLF) is presently limited to aircraft components with low sweep and Reynolds number, primarily due to crossflow instabilities

Wing / Fuselage
Honda Jet

Winglet
Boeing 737 MAX

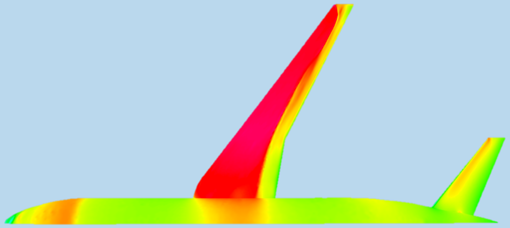
Nacelle
Boeing 787

CATNLF Concept Development

NASA Laminar Flow Design Method

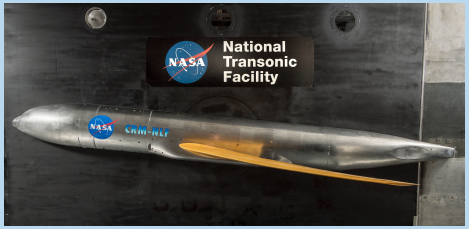
Crossflow Attenuated NLF (CATNLF) design method changes the shape of airfoils to obtain pressure distributions that delay transition by damping crossflow instabilities

Computational Study



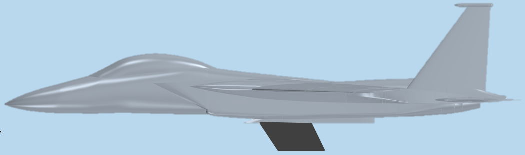
Goal: To develop technology
Reference: AIAA 2016-4326

Wind Tunnel Test



Goal: To confirm computations
References: AIAA 2017-3058, AIAA 2019-3292

Flight Test



Goal: To advance technology
Reference: AIAA 2021-0173

Wind Tunnel Test

Goal: To confirm computations
References: AIAA 2017-3058, AIAA 2019-3292

Test Objectives:

1. Validate the CATNLF design methodology and analysis tools
2. Characterize the National Transonic Facility (NTF) laminar flow testing capabilities
3. Establish best practices for laminar flow wind tunnel testing

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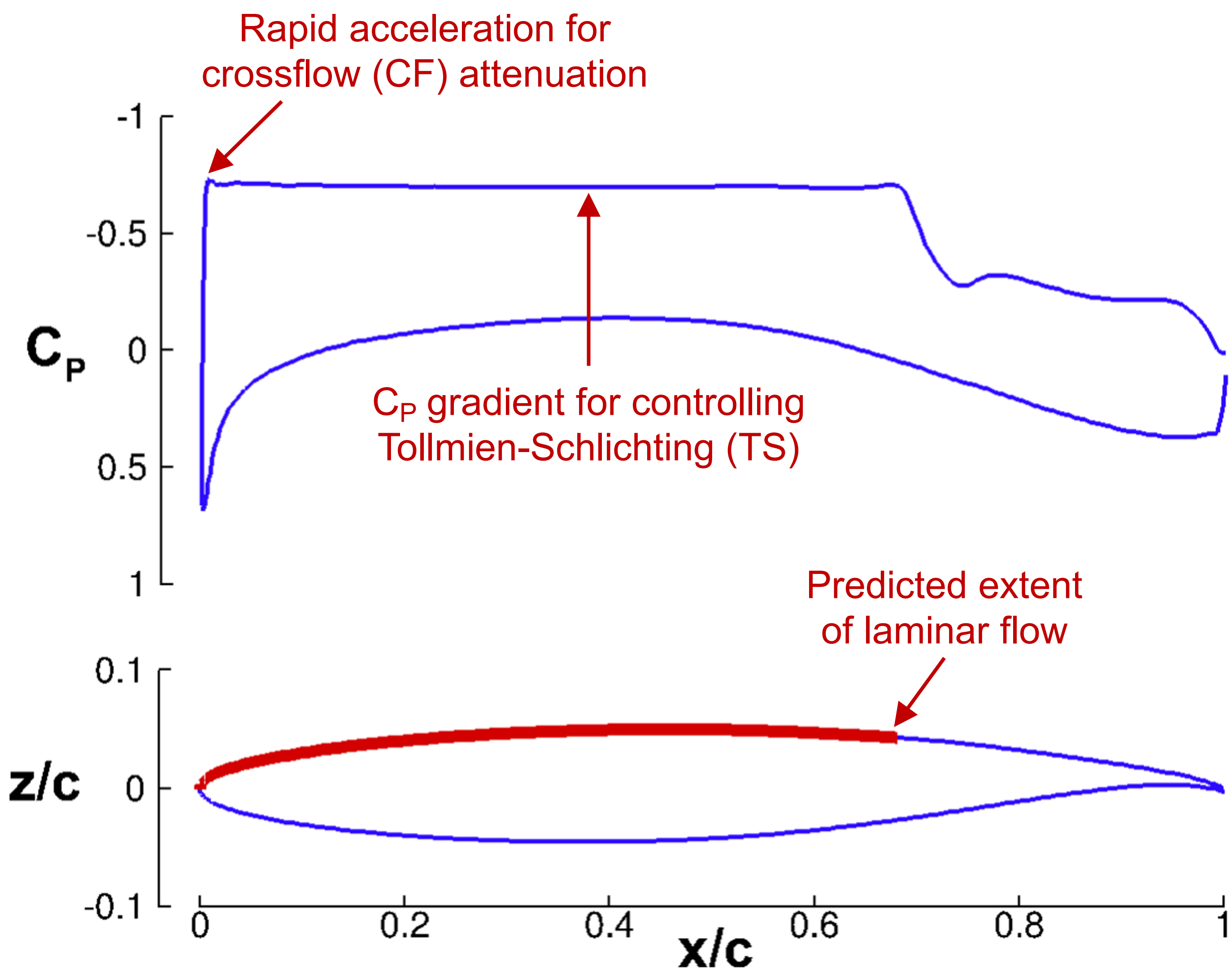
CATNLF Transition Delay Method



CATNLF Analysis Tools

- **Design Module: *CDISC***

  Applies knowledge-based design rules to change geometry to match target pressure distributions

- **Flow Solver: *USM3D***

  Solves Navier-Stokes equations on unstructured tetrahedral grid

- **Boundary Layer Profile Solver: *BLSTA3D***

  Calculates boundary layer velocity and temperature profiles based on chordwise pressure distribution assuming conical flow

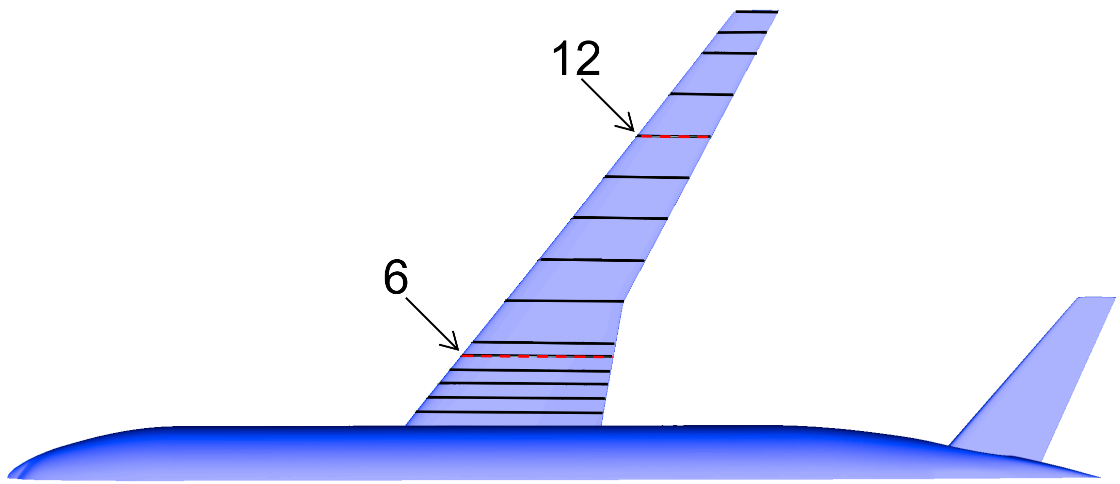
- **Boundary Layer Stability Analysis: *LASTRAC***

  Stability analysis and transition prediction using e^N Linear Stability Theory method with compressibility effects

Model Configuration

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

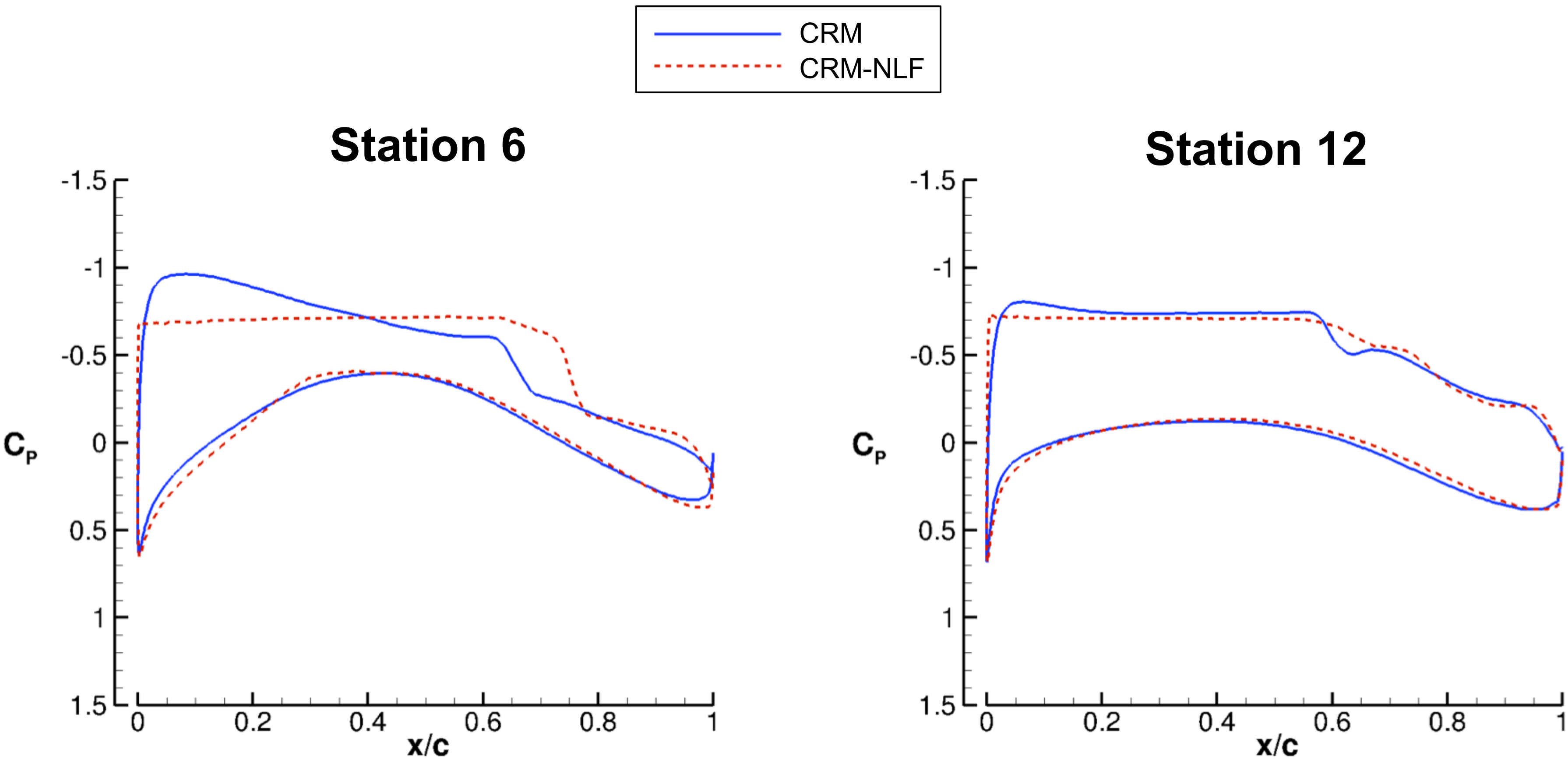
Model is a variant of the Common Research Model (CRM) referred to as the Common Research Model with Natural Laminar Flow (CRM-NLF)



Pressure Distributions

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

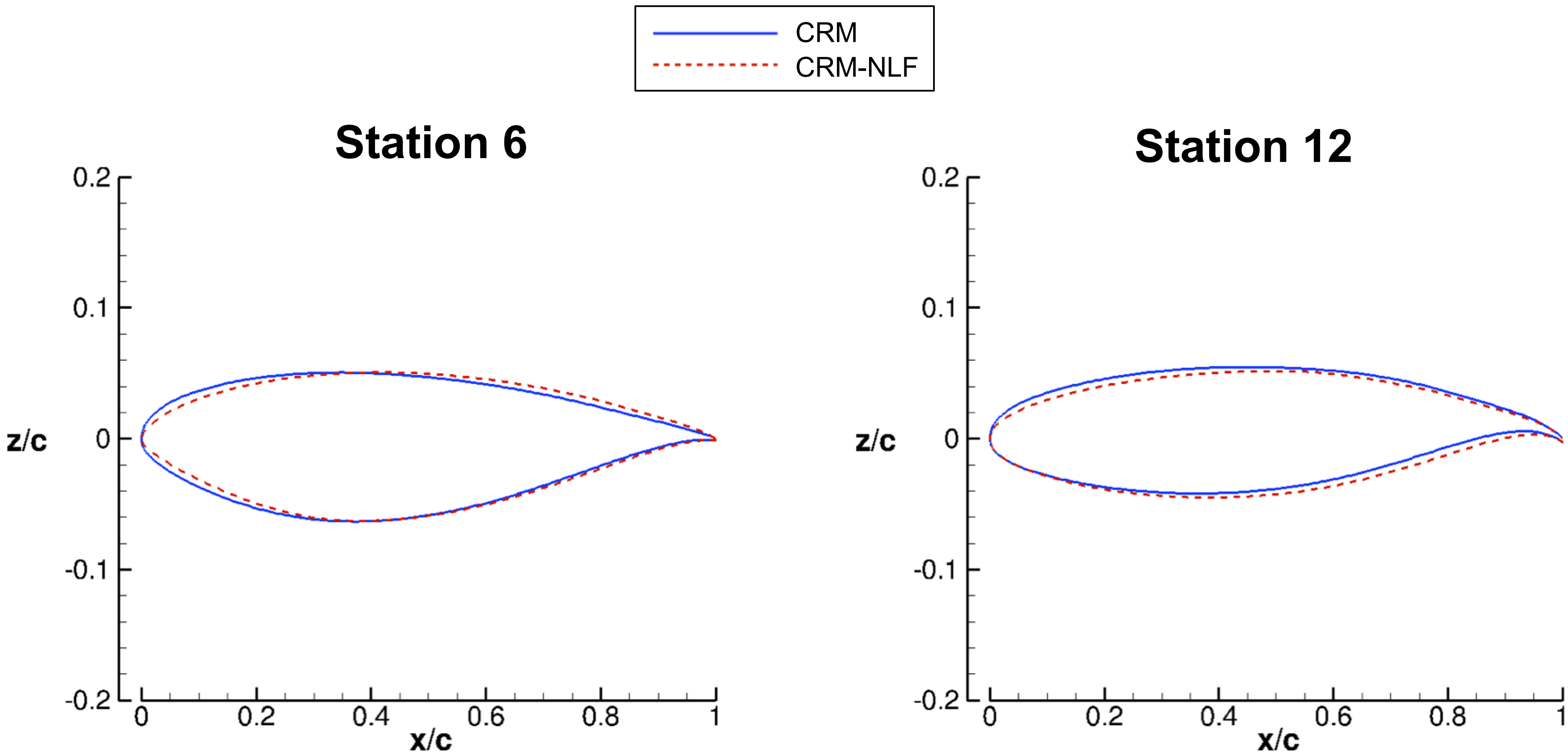
Key features of CATNLF method are obtained in CRM-NLF design



Airfoil Geometry

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

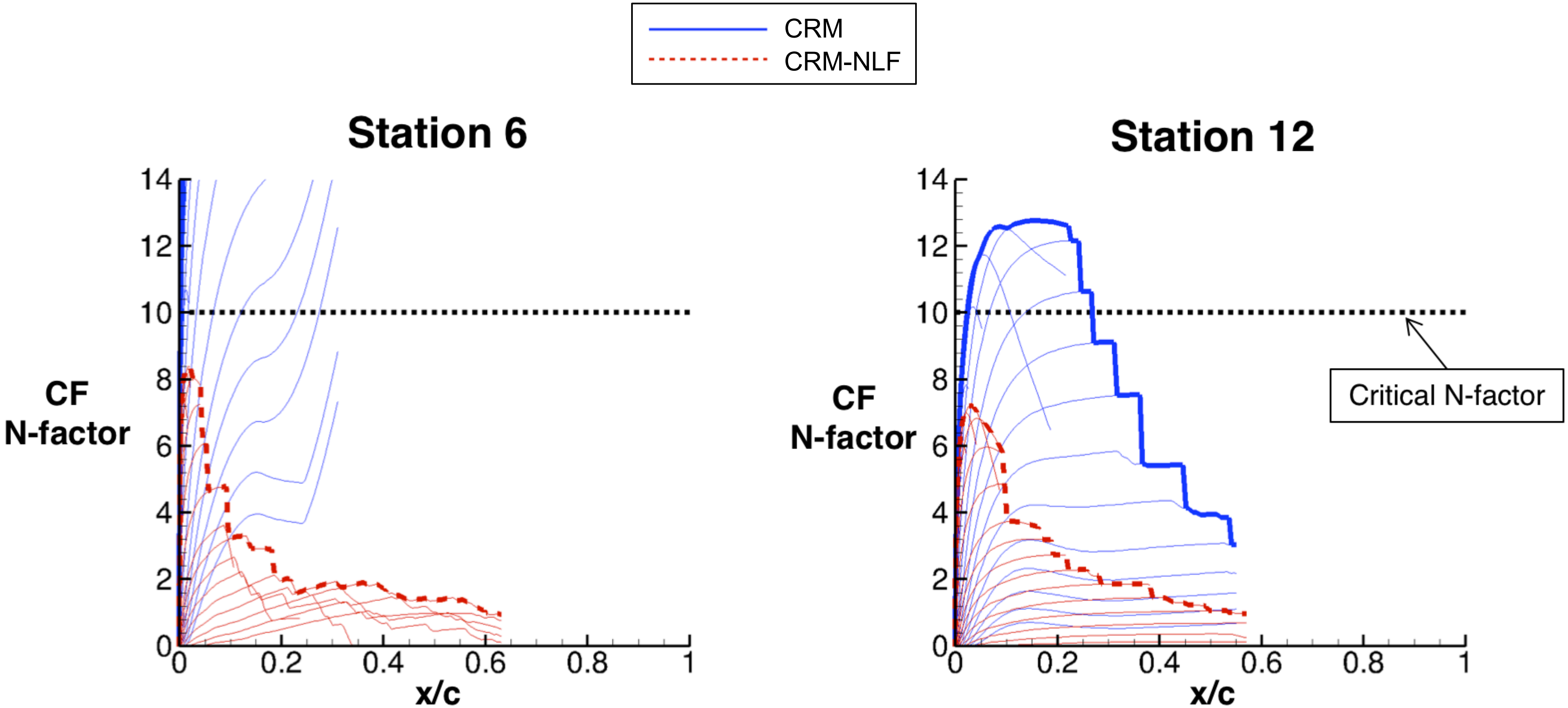
Largest change needed near leading edge on inboard airfoils



Crossflow Stability Analysis

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

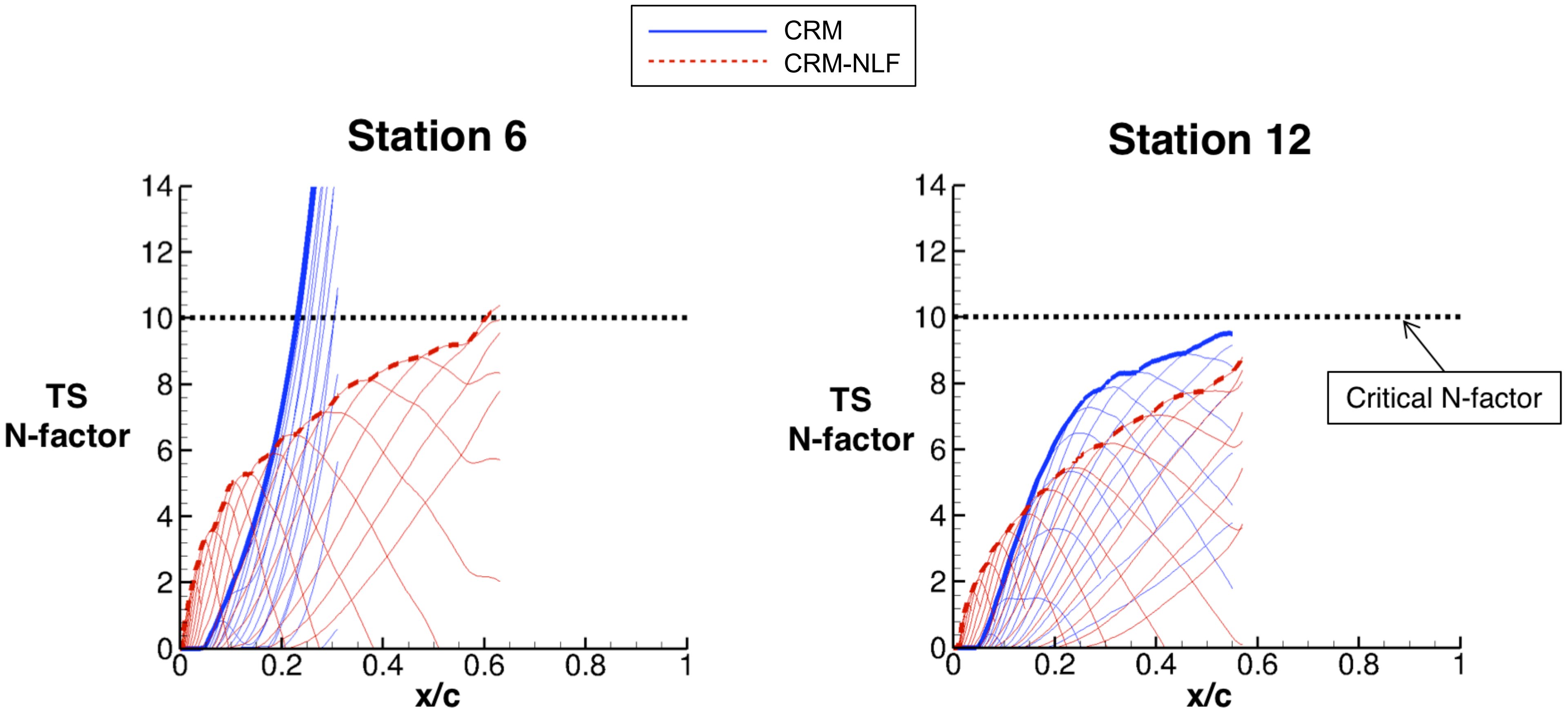
Significant damping of CF near leading edge on CRM-NLF



Tollmien-Schlichting Stability Analysis

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

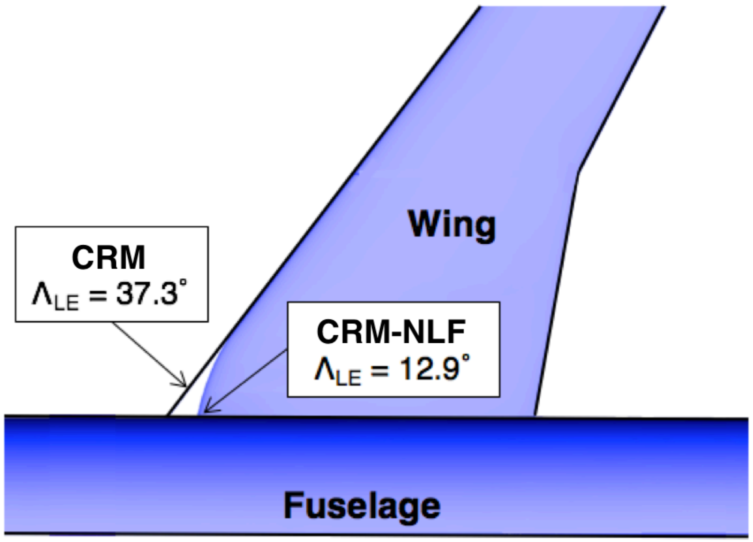
Gradual growth of TS to desired transition location on CRM-NLF

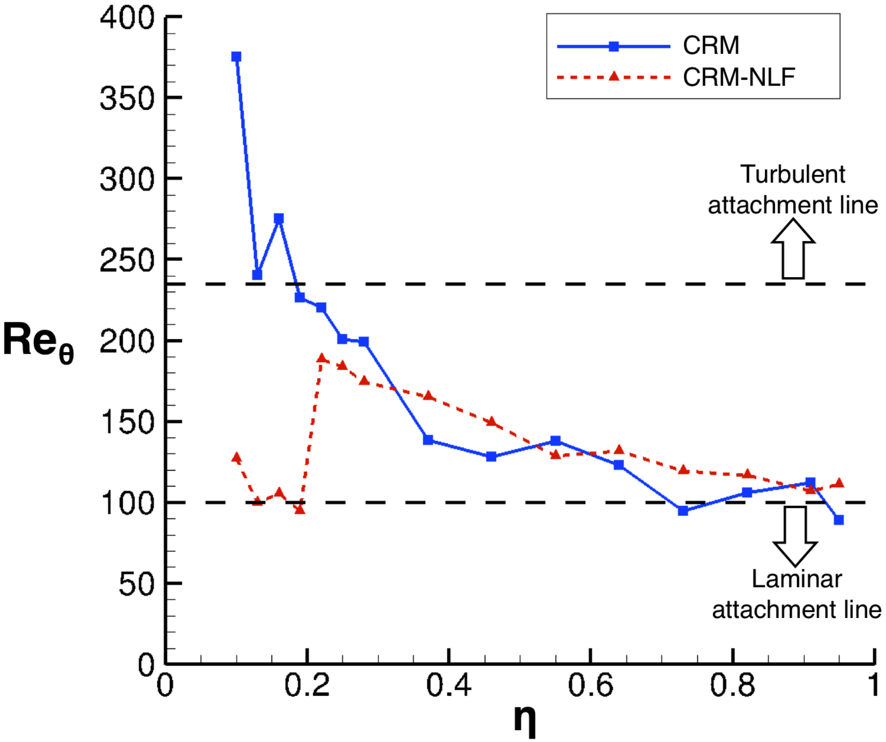


Model Design Results: Attachment Line Control

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

Attachment line contamination is addressed with reduced sweep inboard

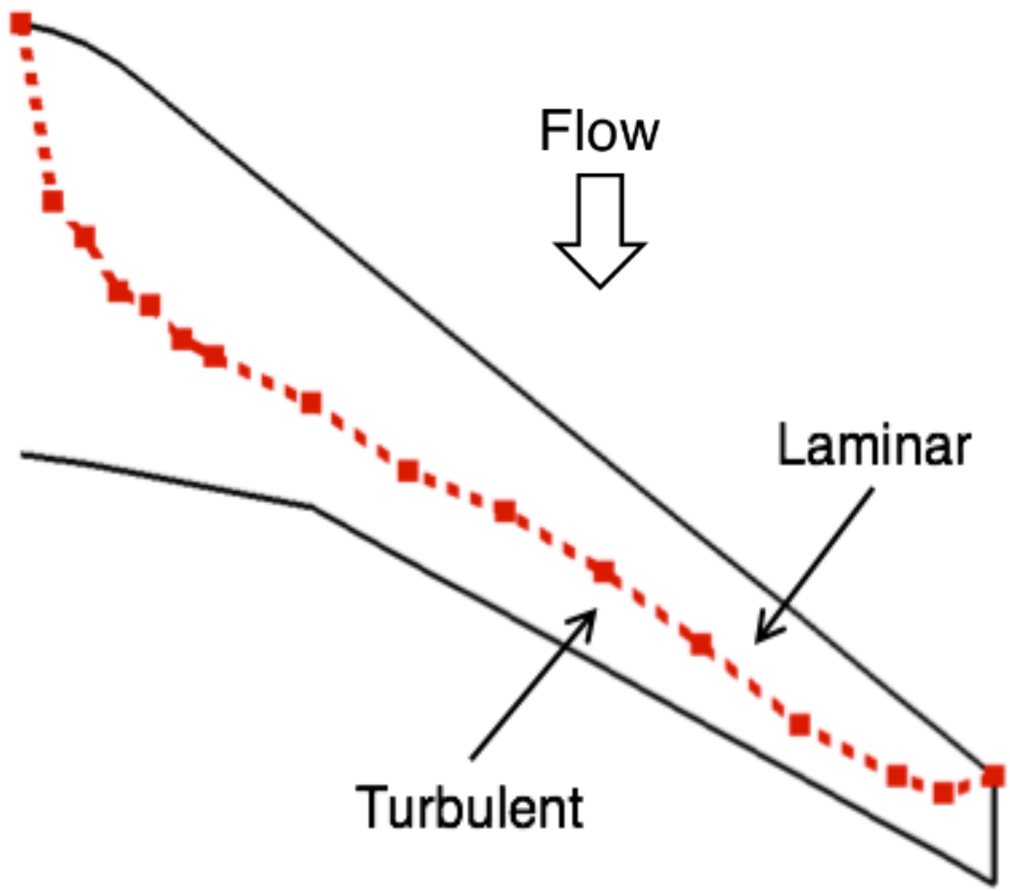




Model Design Results: Design Transition Front

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

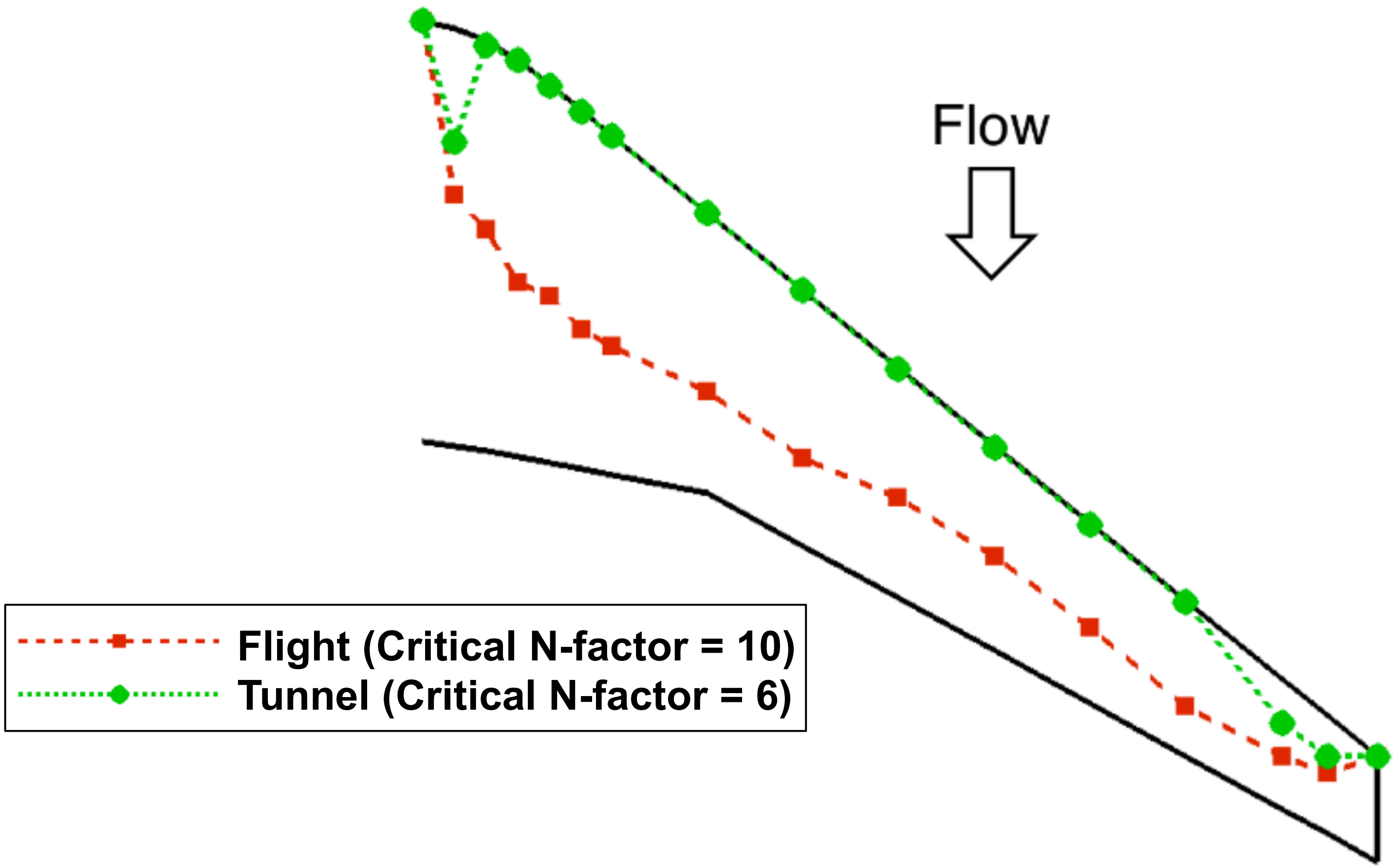
Laminar flow on 56% of wing at design condition (critical N-factor = 10)



Model Design Results: Tunnel Transition Front

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

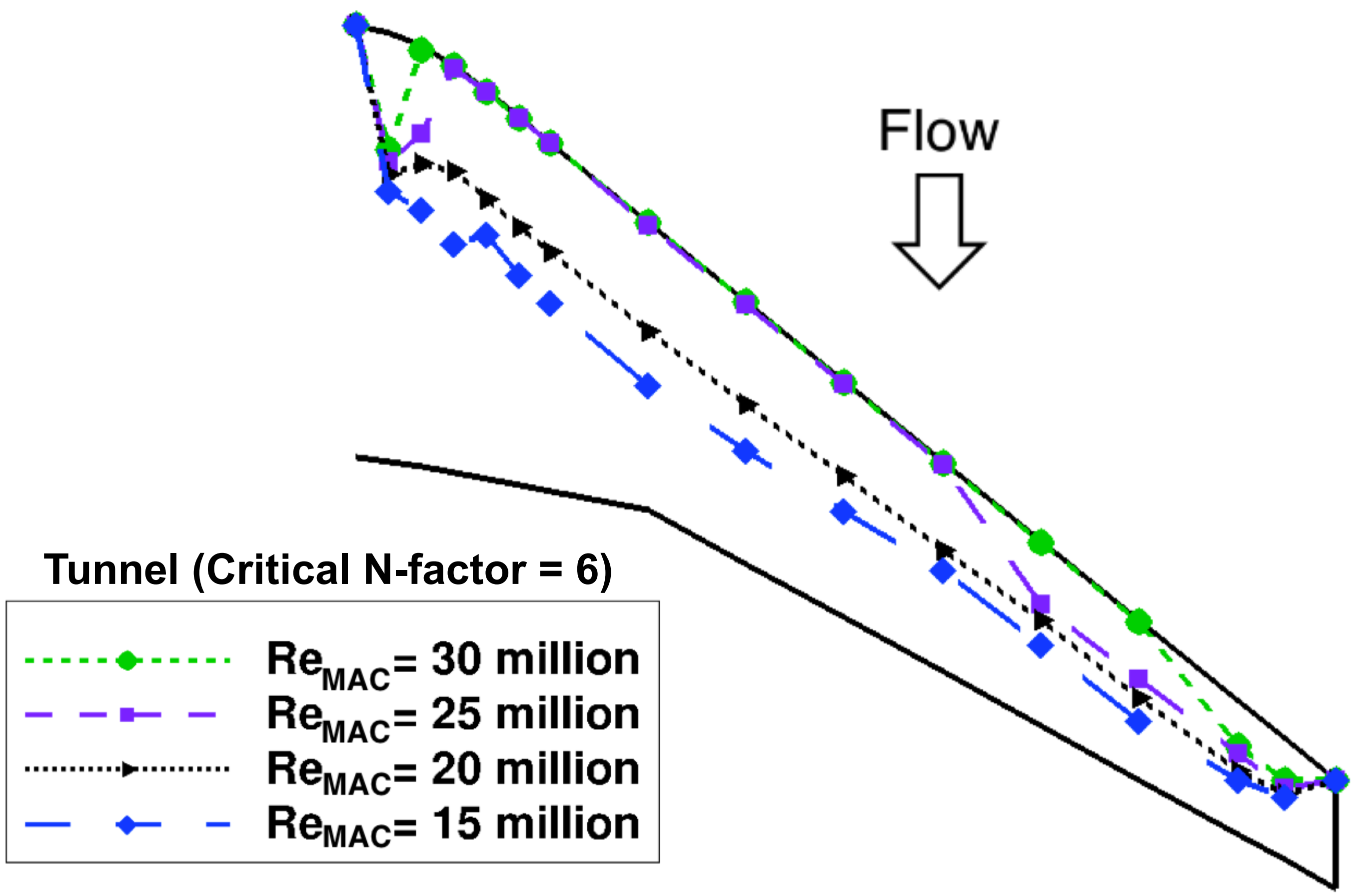
Environment (represented by critical N-factor) effects extent of laminar flow



Model Design Results: Tunnel Transition Front

Design Conditions: Mach = 0.85, Re_{MAC} = 30x10^6, C_L = 0.5

Reducing Re_{MAC} in wind tunnel environment will extend laminar flow



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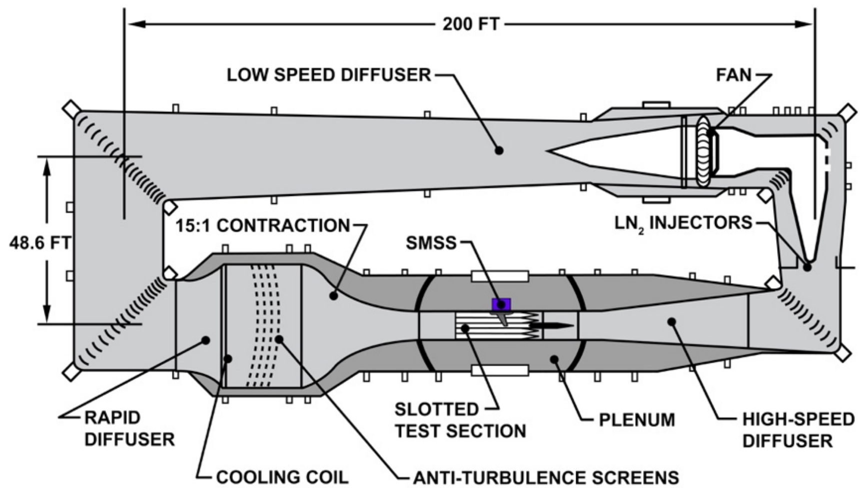
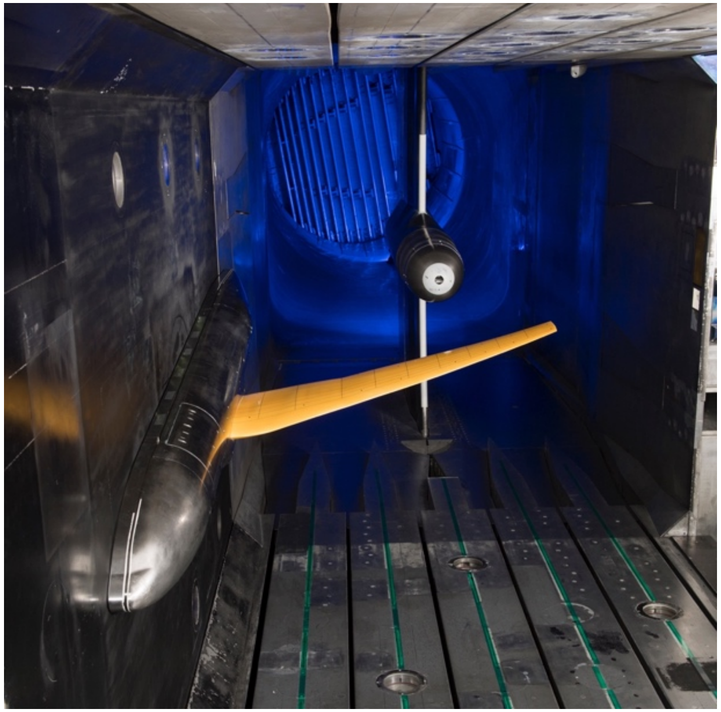
Facility Description



- Test completed in October 2018 in the National Transonic Facility (NTF) at the NASA Langley Research Center
- NTF is a pressurized cryogenic closed-circuit, continuous-flow, fan-driven wind tunnel
- Motivation for testing in the NTF:
  - Flight Reynolds numbers for relevant laminar flow data
  - Semispan testing capability for reducing unit Reynolds numbers
  - Acceptably low turbulence levels for laminar flow testing

Instrumentation and Measurements

- 5.2% scale semispan model
  - Semispan length = 60.2 inches
  - Reference chord = 14.3 inches
- Data acquired:
  - Surface pressure
  - Transition visualization
  - Force and moment
  - Model deformation

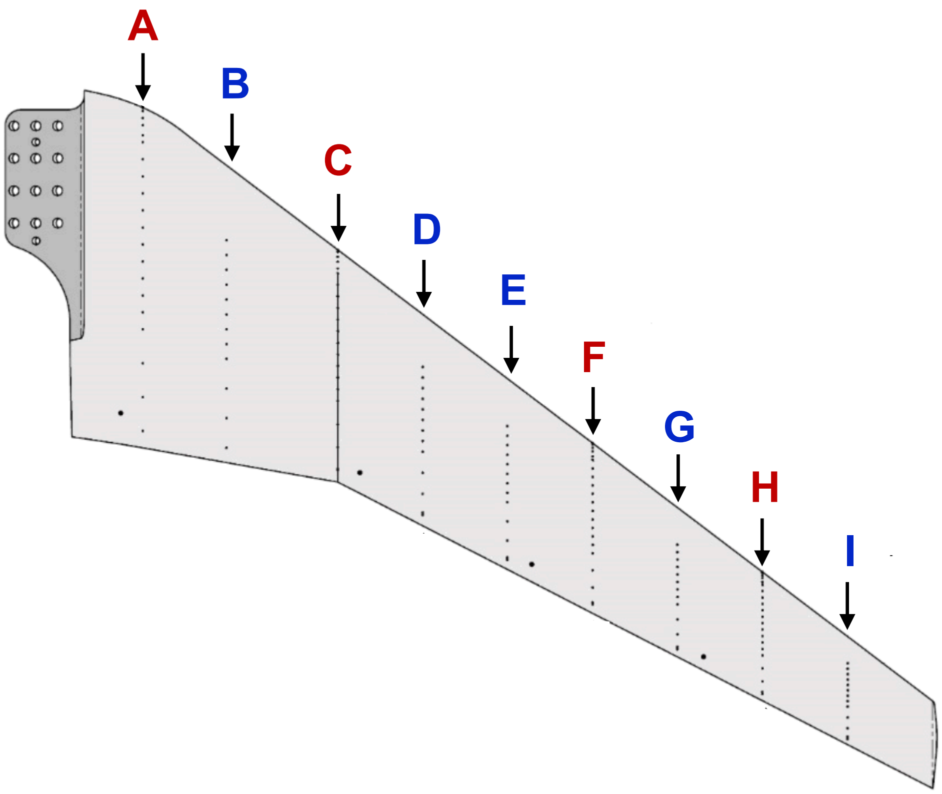


Primary Test Conditions

Mach	α (deg.)	T_T (°F)	q_∞ (psfa)	Re_{MAC} (million)
0.86	1.5 to 3.0	+40	1180 to 1780	10.0 to 15.0
		-50	1120 to 1800	12.5 to 20.0
		-150	1200 to 1800	20.0 to 30.0

Surface Pressure Data

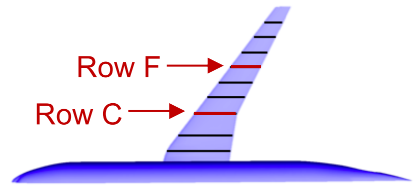
- Surface pressure data essential for CATNLF method evaluation
- Wing has 230 pressure ports arranged in 9 chordwise rows
- Leading-edge pressure ports only on 4 rows to avoid loss of laminar flow at every row

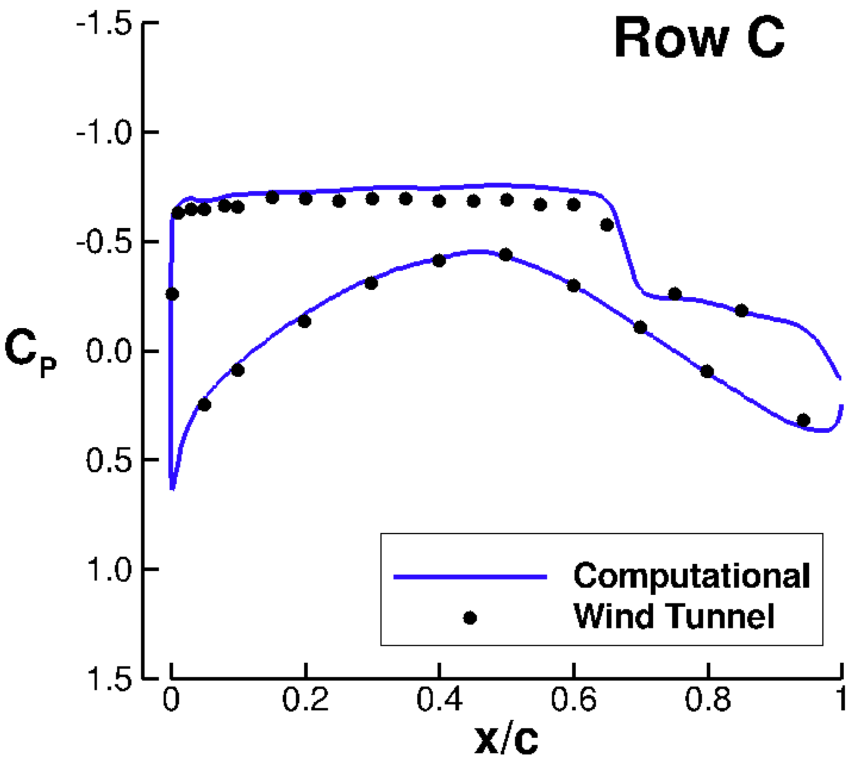


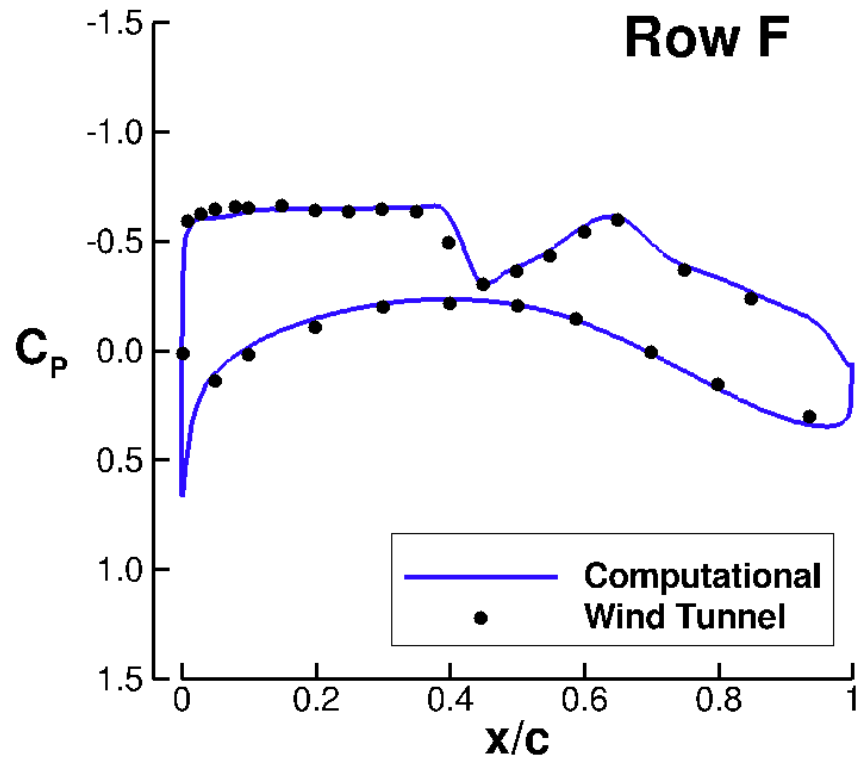
Surface Pressure Data

Tunnel Conditions: M = 0.86, Re_{MAC} = 15x10^6, α = 2.0 deg.

CATNLF pressure architecture obtained on the wind tunnel model

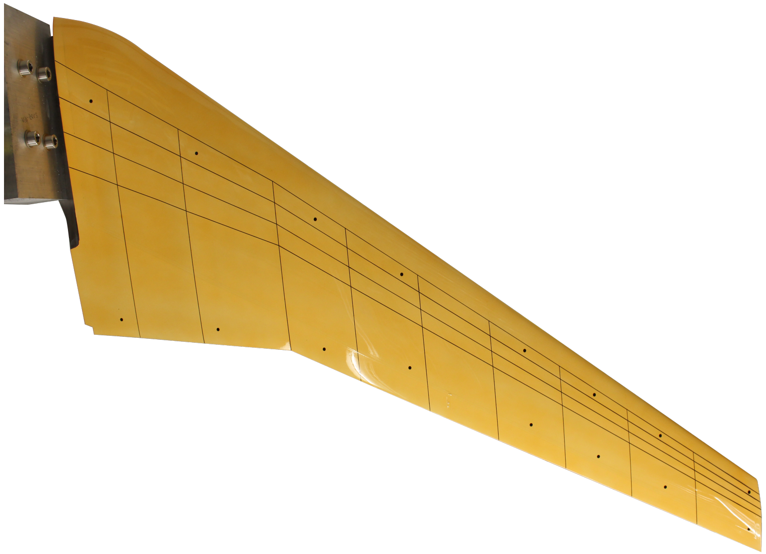






Transition Visualization Data

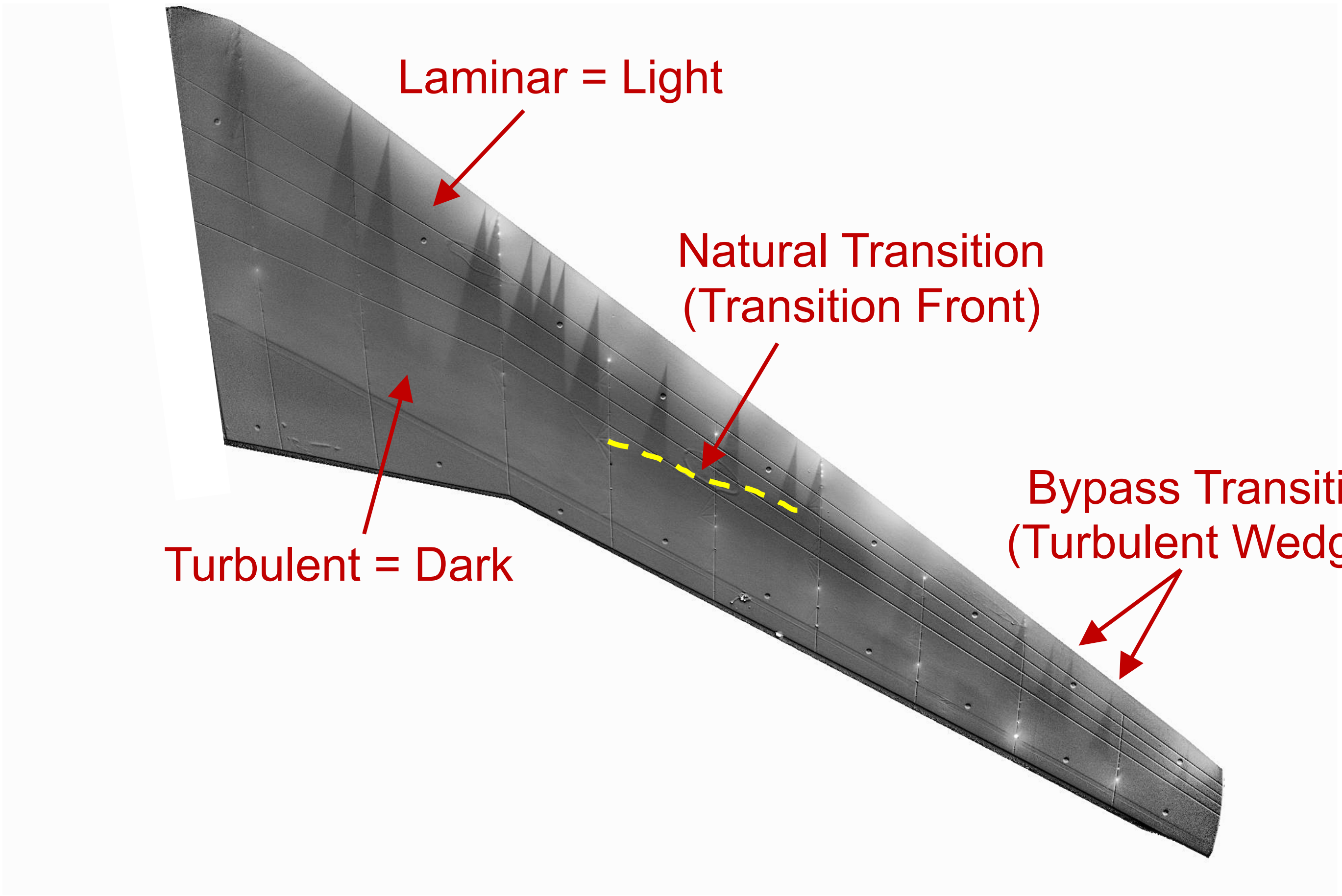
- Temperature Sensitive Paint (TSP) used for transition visualization
- Two methods used to introduce the required TSP temperature gradient
  - Rapid Liquid Nitrogen Injection: Reduces the freestream temperature
  - Carbon-Based Heating Layer: Increases the model temperature [Ref. 1]
- Average surface roughness measured to be ~1 μin prior to testing
- Surface quality maintained during testing by frequently sanding and polishing the wing



[Ref. 1] AIAA 2019-2191

Transition Visualization Data

TSP images show regions of laminar flow on the wing upper surface



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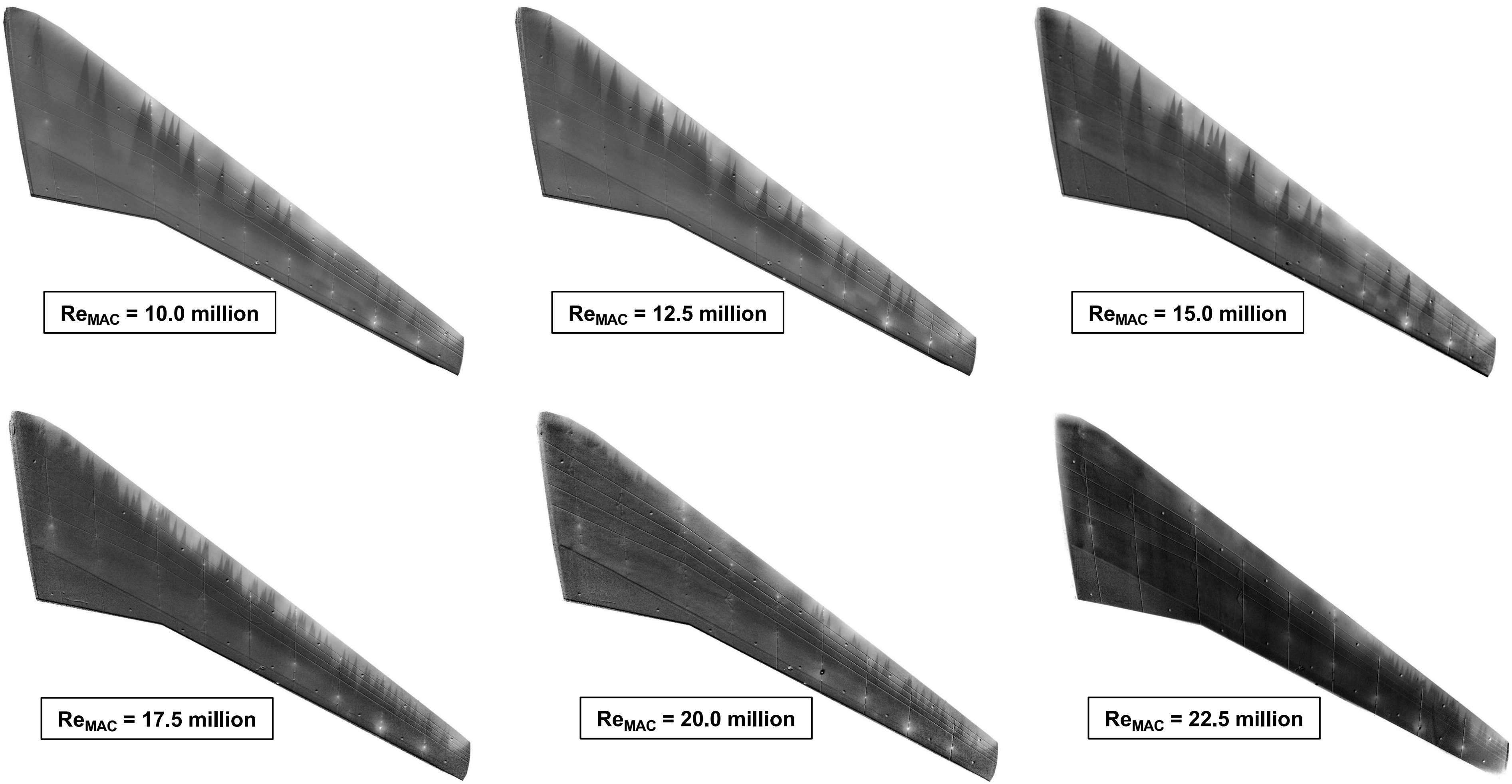
TSP Images: Reynolds Number Sweep

Tunnel Conditions: M = 0.86, α = 1.5 deg.

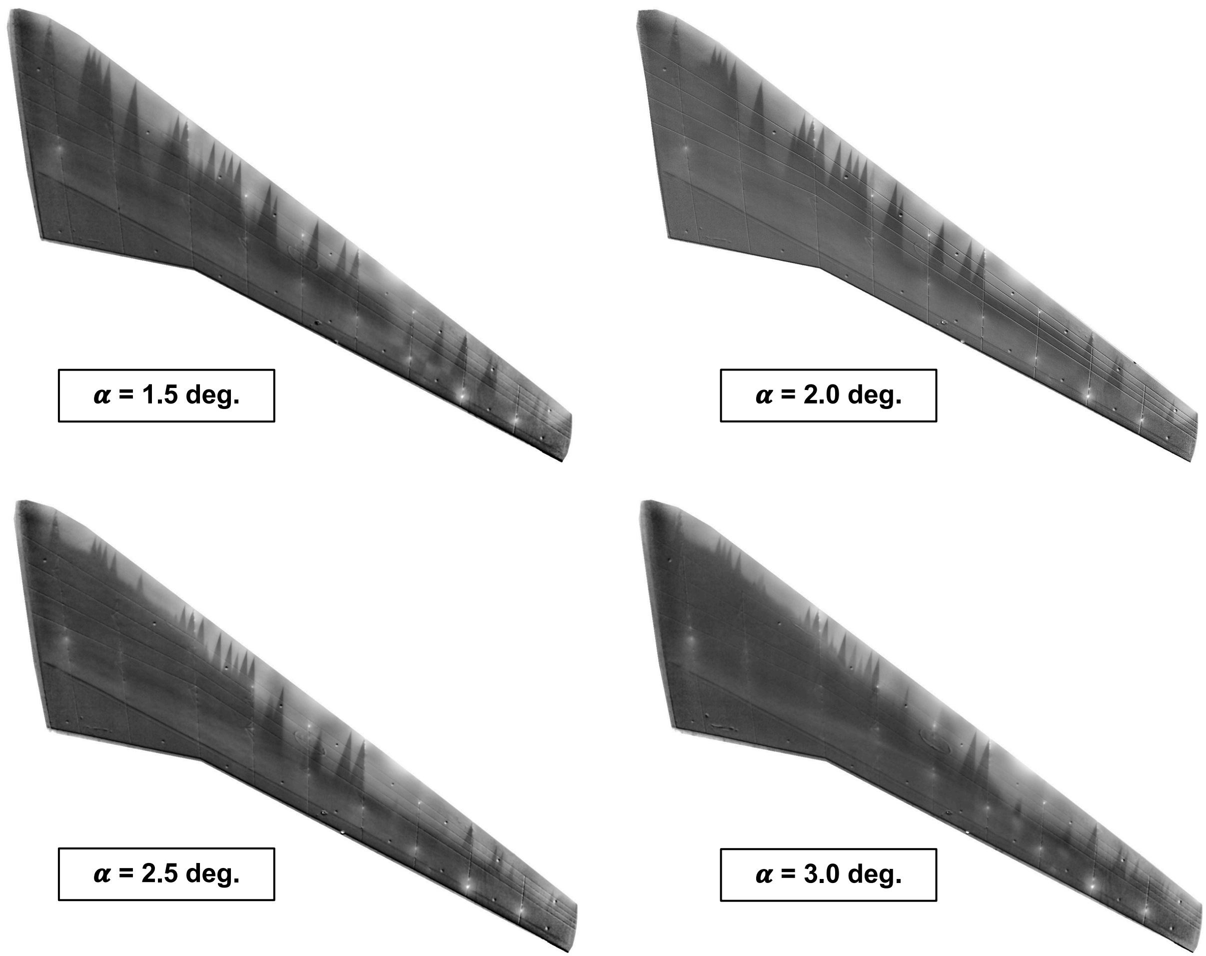
Turbulent wedges at high Reynolds numbers make analysis challenging



TSP Images: Alpha Sweep

Tunnel Conditions: M = 0.86, Re_{MAC} = 15x10^6

Laminar flow maintained across alpha sweep



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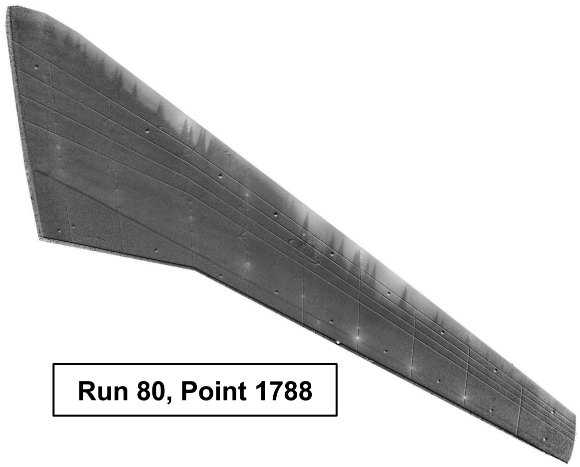
Bypass Transition During Repeat Points

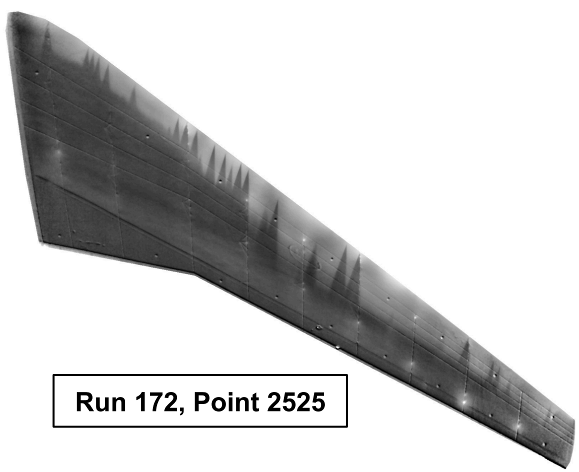
Tunnel Conditions: M = 0.86, Re_{MAC} = 15x10^6, α = 2.5 deg.

Repeat points vital to ensure best possible image was acquired



Run 80, Point 1788

Run 92, Point 1896



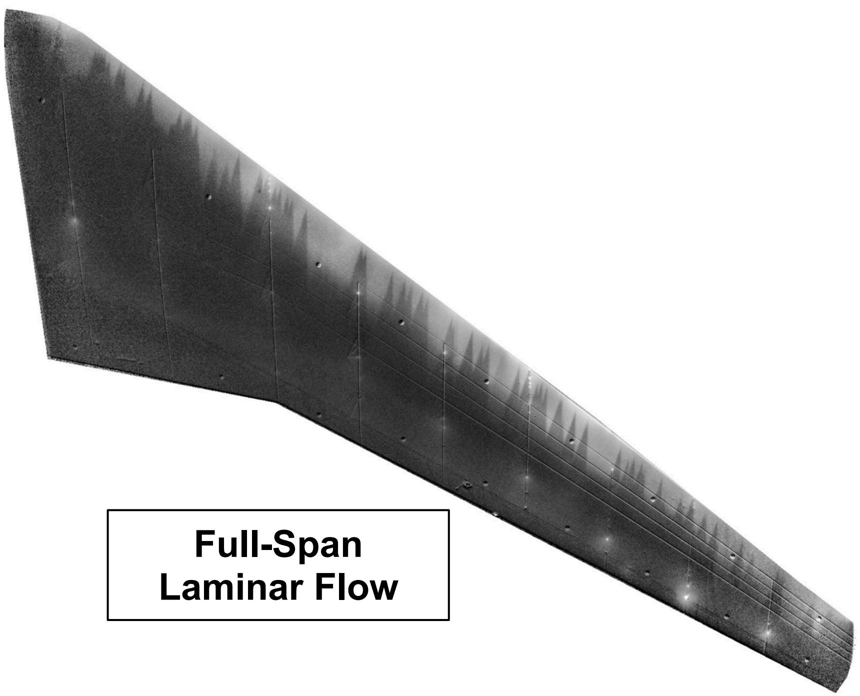
Run 172, Point 2525

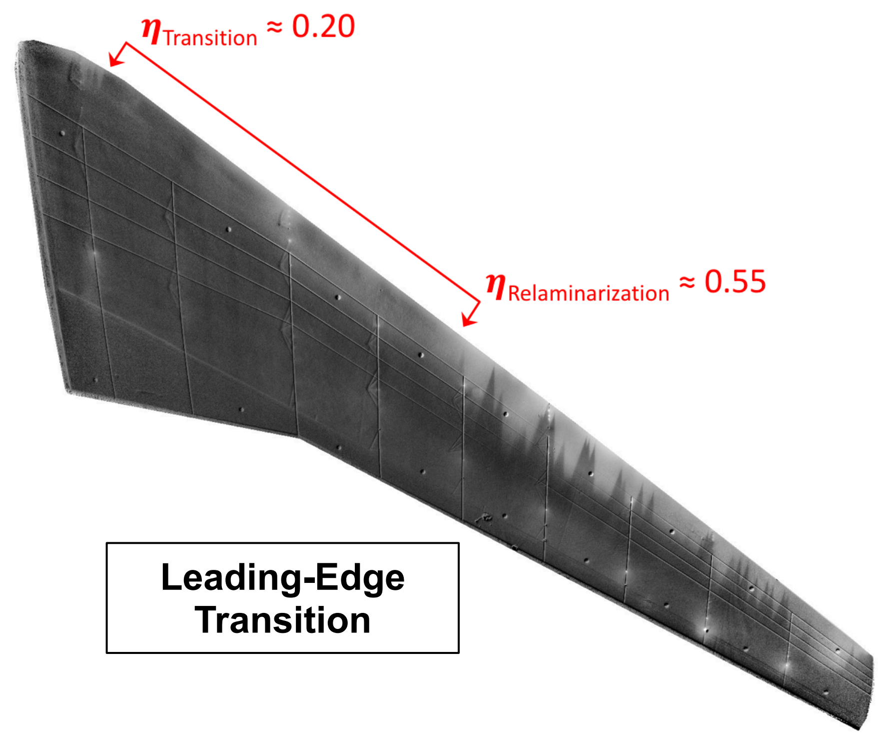
Run 181, Point 2563

Attachment Line Bypass Transition

Tunnel Conditions: M = 0.86, Re_{MAC} = 17.5x10^6, α = 2.0 deg.

Repeat images help determine if leading-edge transition is due to attachment line bypass transition

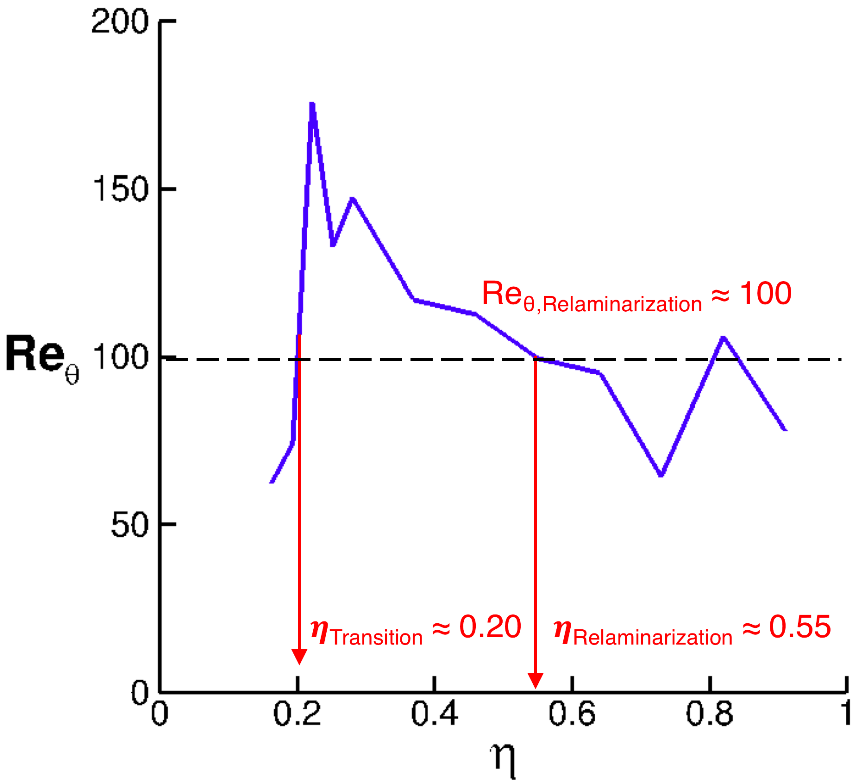


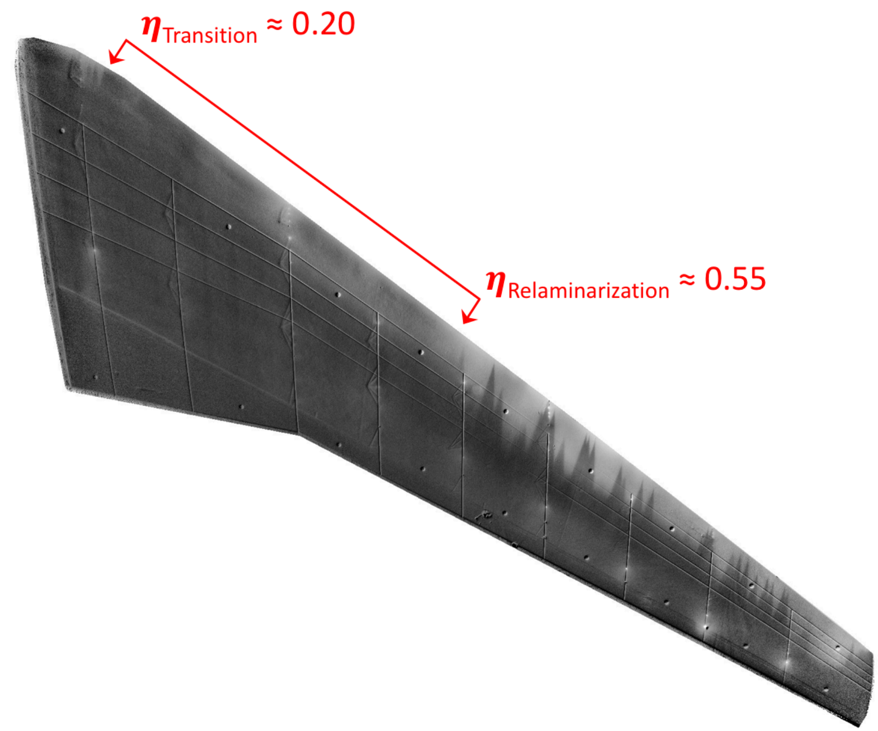


Attachment Line Bypass Transition

Tunnel Conditions: M = 0.86, Re_{MAC} = 17.5x10^6, α = 2.0 deg.

Examples of attachment line bypass transition confirm Poll's criteria

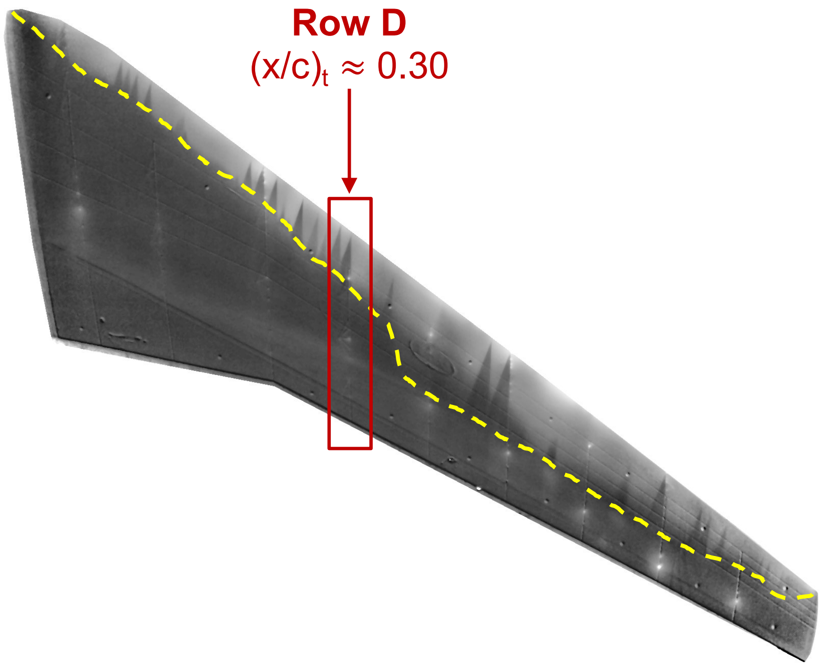


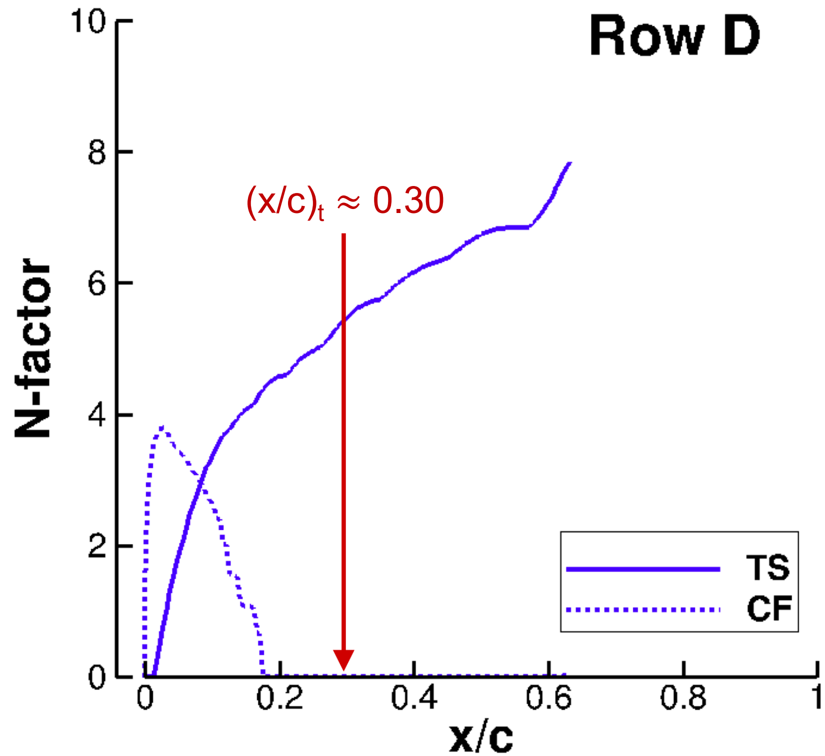


Transition Analysis: TS Transition

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 3.0 deg.

Experimental transition location correlated to computational N-factor growth suggests TS transition

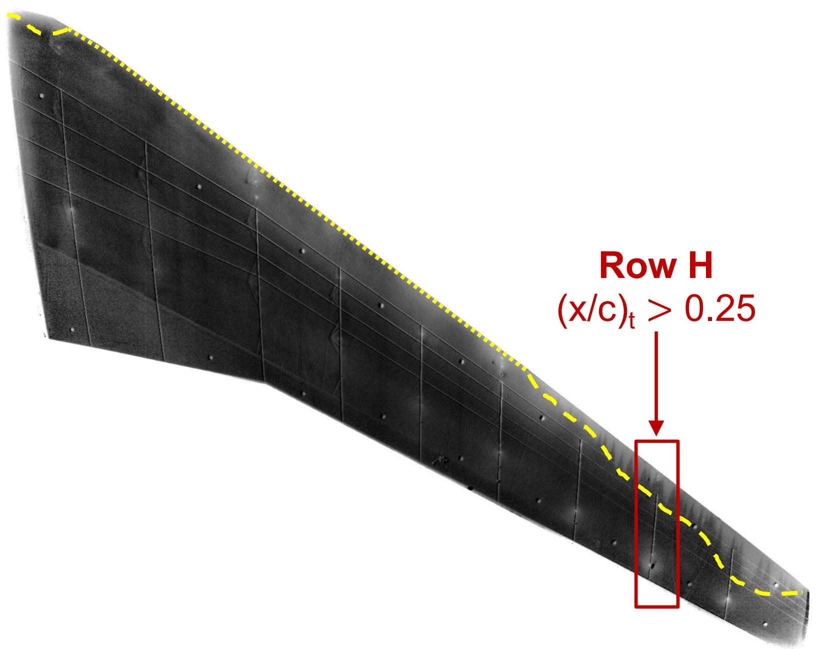


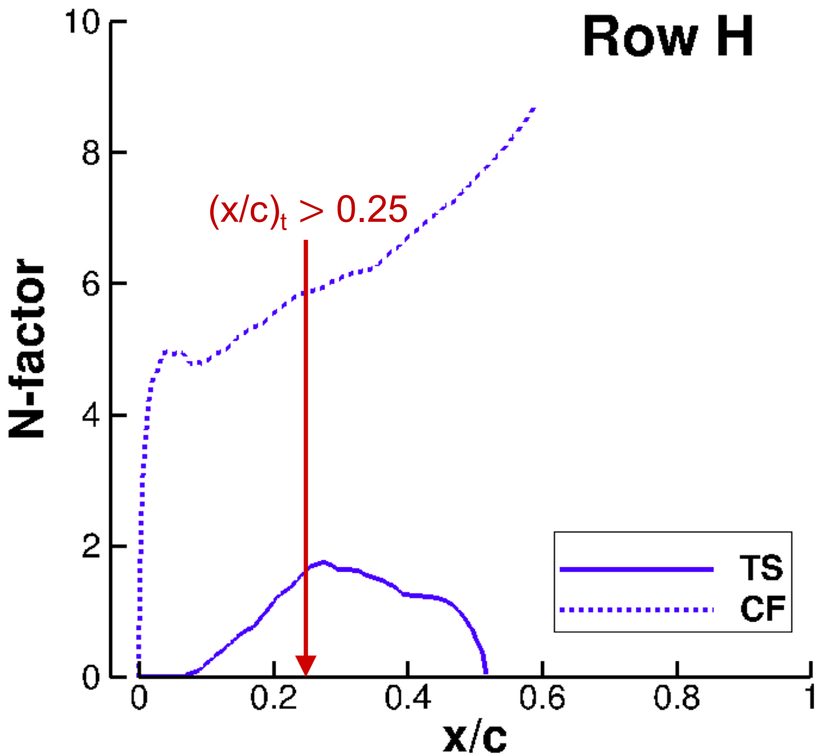


Transition Analysis: Midchord CF Transition

Tunnel Conditions: M = 0.86, Re_{MAC} = 22.5x10^6, α = 1.5 deg.

Some images with significant bypass transition can still be used for transition mechanism assessment



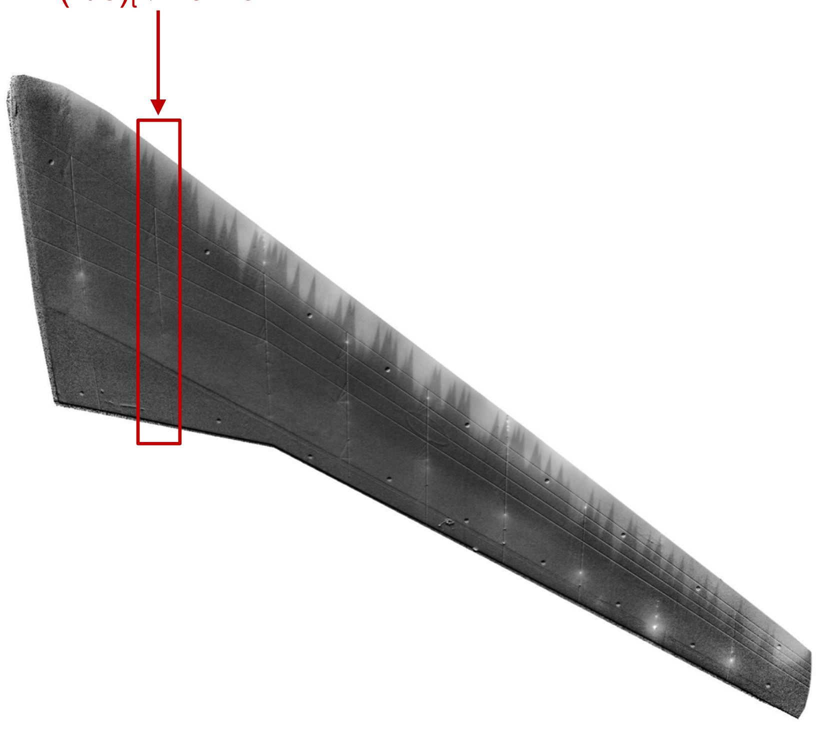


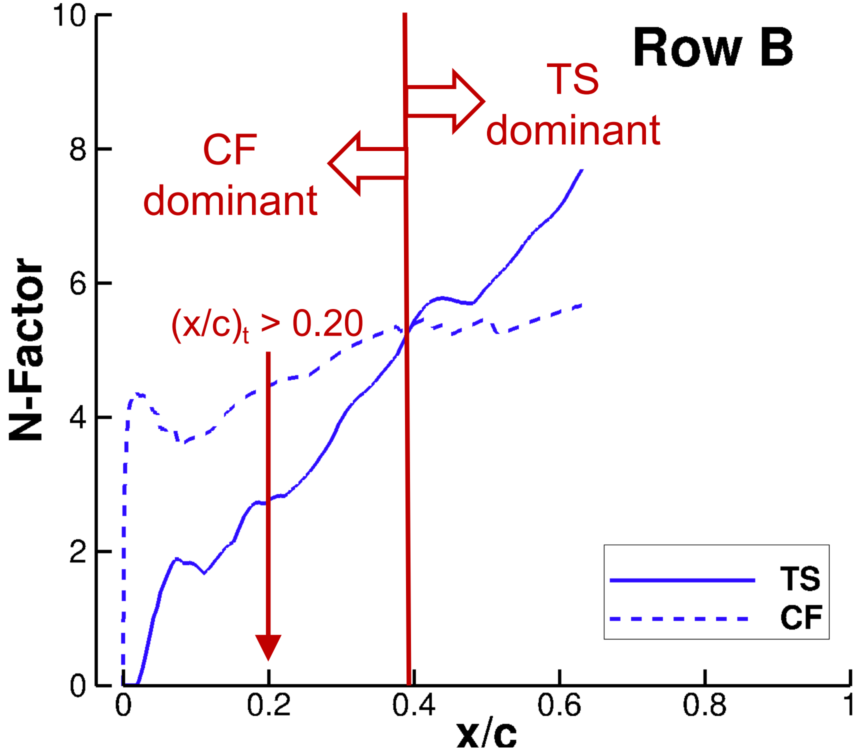
Transition Analysis Limited by Bypass

Tunnel Conditions: M = 0.86, Re_{MAC} = 17.5x10^6, α = 1.5 deg.

N-factor growth often varies along the chord such that the natural transition location is required to know which mechanism is critical

Row B
$(x/c)_t > 0.20$





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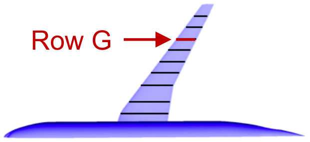
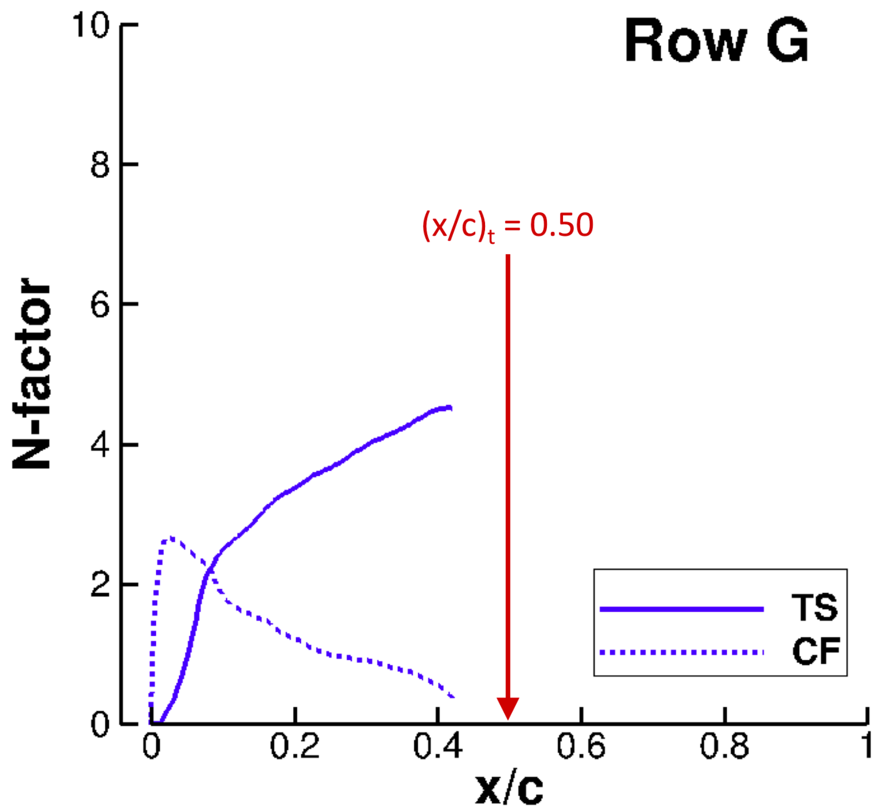
Challenges with Analysis: Unsteady Pressures

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 2.5 deg.

Some stability analysis calculations terminated ahead of the experimental transition location

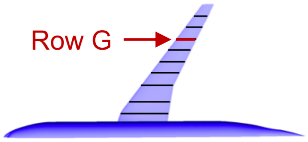


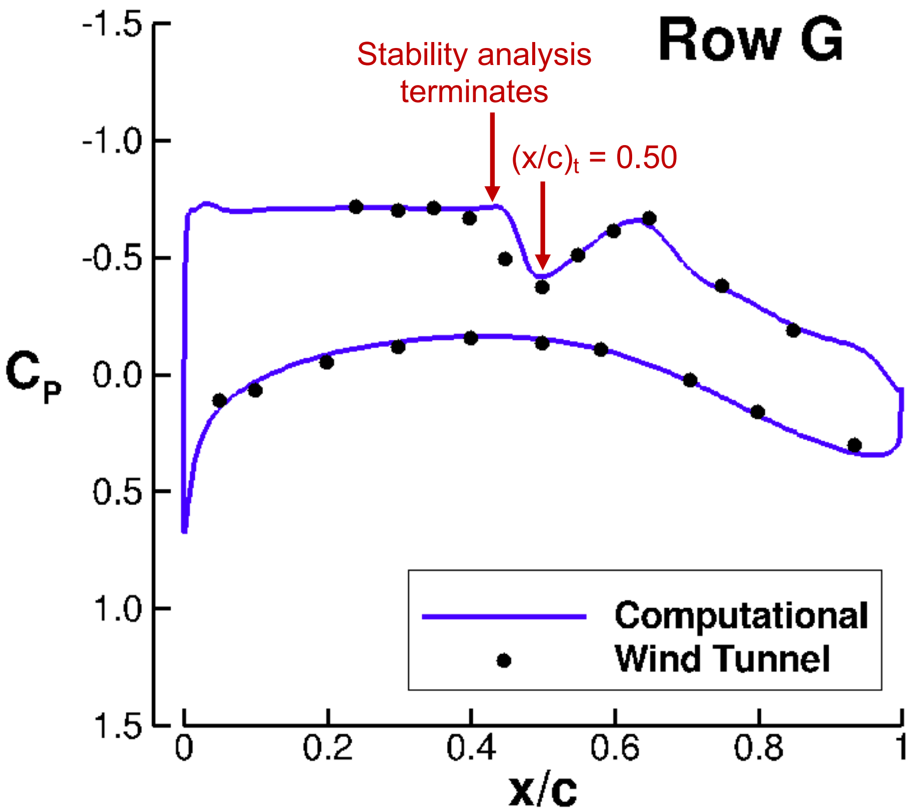


Challenges with Analysis: Unsteady Pressures

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 2.5 deg.

Experimental transition location occurs aft of the shock

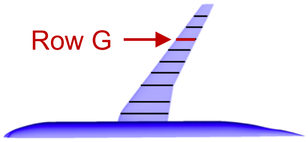


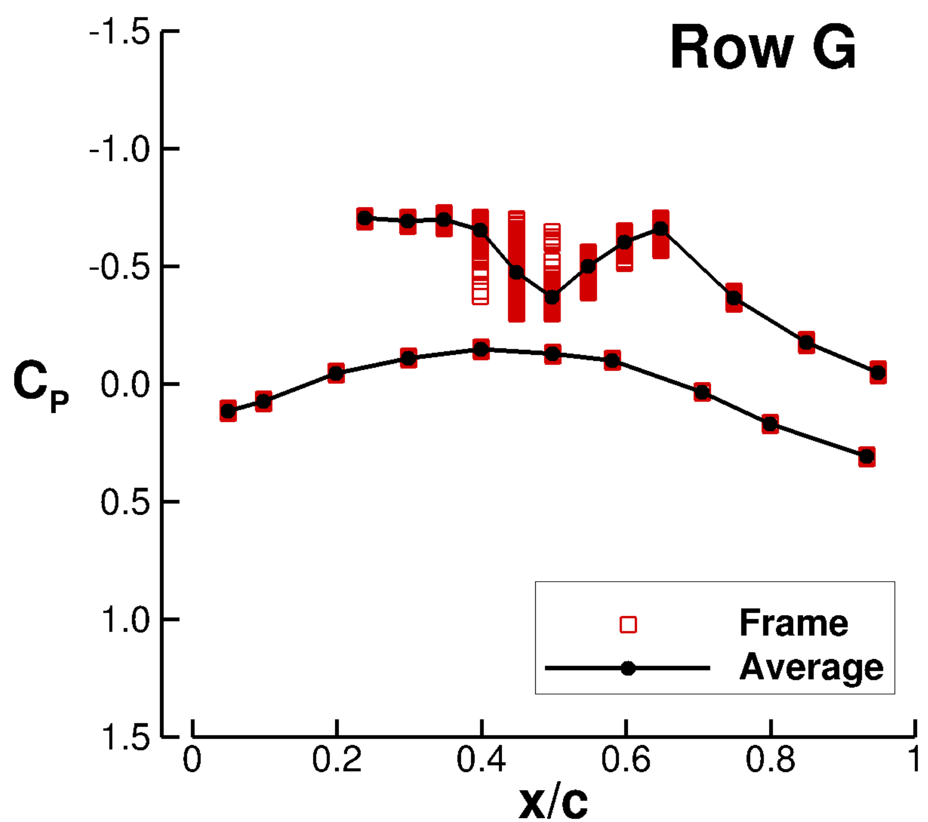


Challenges with Analysis: Unsteady Pressures

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 2.5 deg.

Experimental frame data showed significant variation in pressure readings over the midchord region

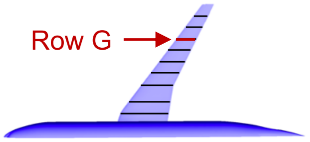


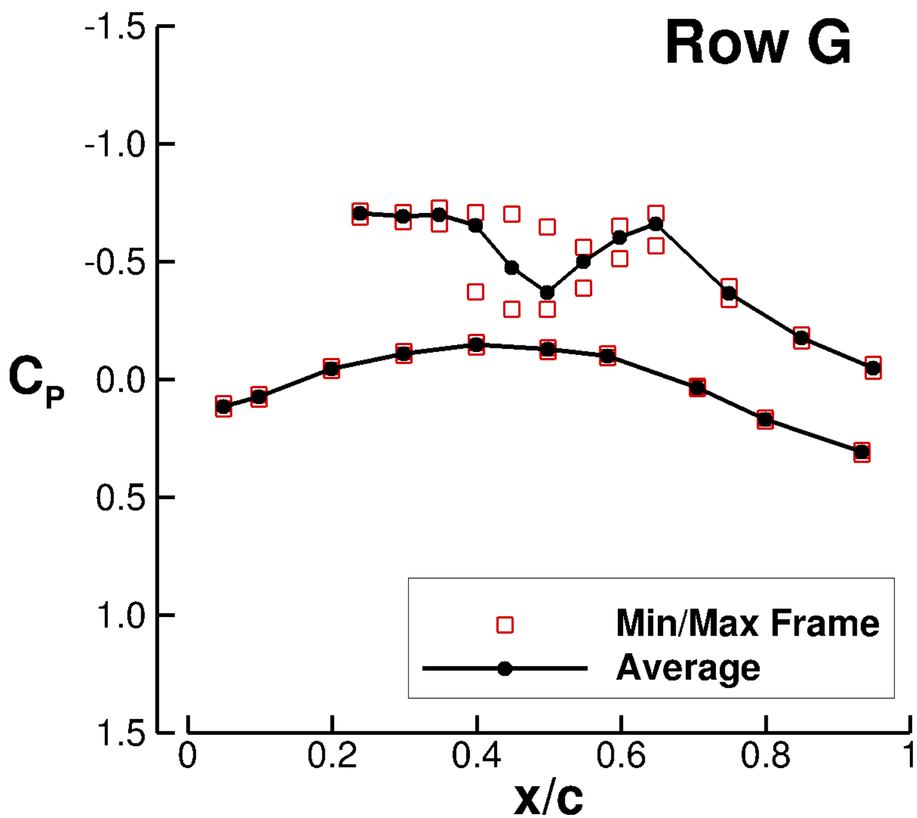


Challenges with Analysis: Unsteady Pressures

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 2.5 deg.

Significant variation in pressure readings can be explained by pressure distributions from individual frames





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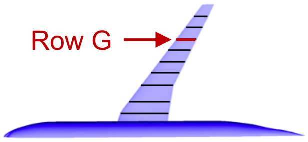
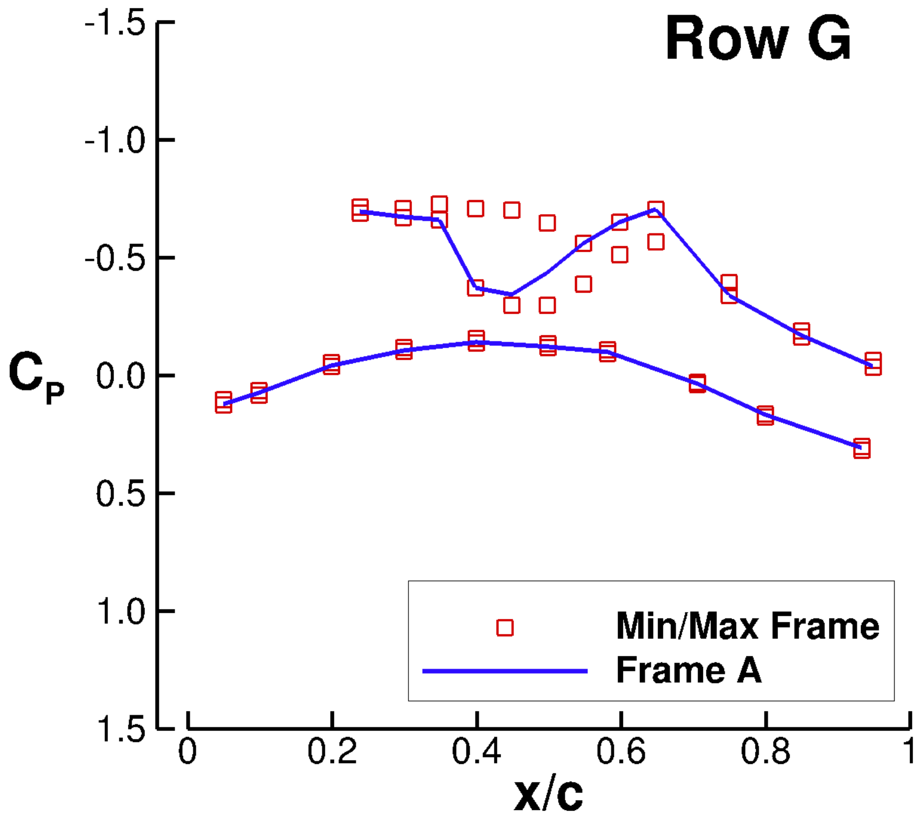
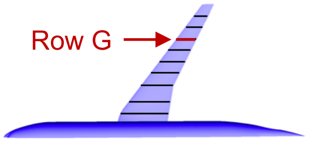


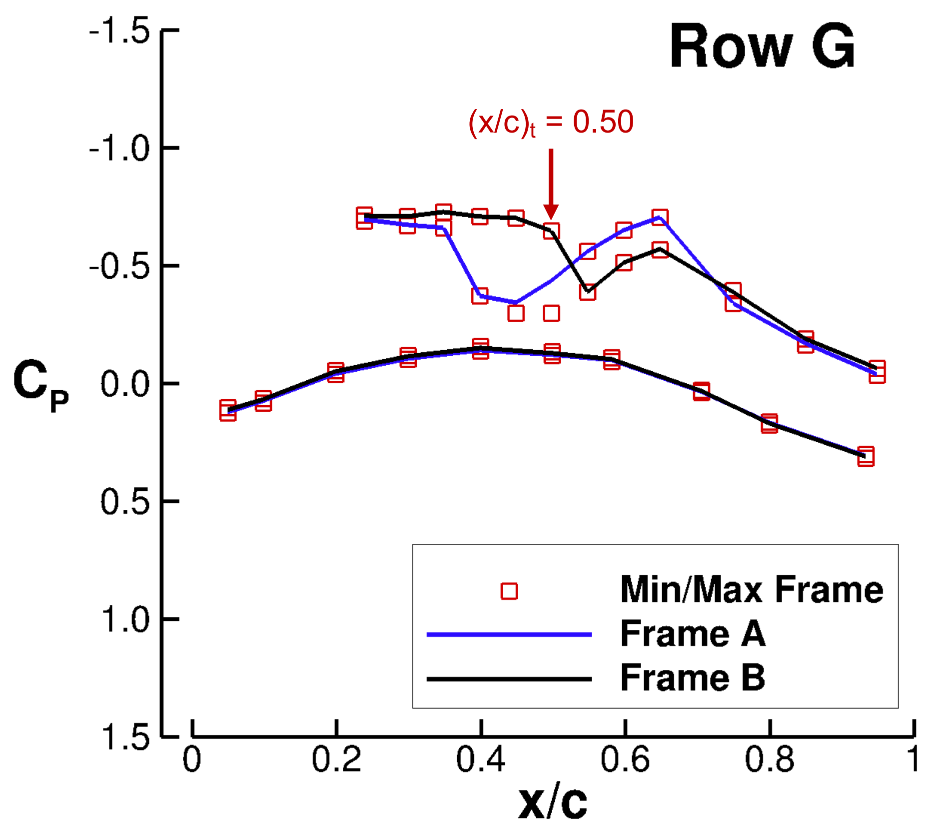


Challenges with Analysis: Unsteady Pressures

Tunnel Conditions: M = 0.86, Re_{MAC} = 15.0x10^6, α = 2.5 deg.

Pressure distributions from individual frames show shock further aft and provide explanation for aft transition location





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Concluding Remarks

- A test of the CRM-NLF in the NTF was completed in October 2018
- CRM-NLF data used in the 2021 AIAA Transition Modeling Workshop to help promote computational tool advancements
- Challenges with laminar flow data acquisition in a wind tunnel limited high Reynolds number data analysis
- Extents of laminar flow on CRM-NLF nearly double those seen in past NLF experiments at comparable sweep angles
- Positive results from CRM-NLF test has led to CATNLF flight test to evaluate transition delay method in flight environment
- Design of CATNLF flight test article completed [Ref: AIAA 2021-0173]

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